Design for a Solar Sail Demonstration Mission

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Abstract. Solar sails are an important propellantless propulsion technology that can enable missions requiring very high velocity changes and/or non-Keplerian orbits. The New Millennium Program has funded this design study for a near term solar sail flight demonstration that can verify a specific solar sail technology implementation for use in scientific missions. The baseline design selected is a 3-axis stabilized square sail, 40 meters on a side, with an effective area of 1,400 m^2. The sail surface is comprised of four triangular panels simply supported by four deployable booms. Euler column buckling limits this design to about 20,000 m^2, but four or more of these sails can be linked together as structural modules to obtain sail areas of 80,000 m^2 or larger, still utilizing cantilevered booms and the same deployment system technology that would be validated in the proposed demonstration mission. The attitude control methodology selected for the baseline is to articulate the spacecraft bus on a short boom to shift the center of mass of the flight system relative to the center of pressure, thus achieving pitch and yaw control. Roll control would be achieved through non-propellantless techniques.

INTRODUCTION

A number of important science missions have been identified which require the use of a propellantless propulsion system to enable a constant thrust over an extended mission lifetime. These missions appear on the NASA Roadmap (NASA, 2000). Some example missions are a Solar Polar Imager, the Geostorm early warning system for solar flares (West, 1996), and the Saturn Ring Observer. There are also commercial and military applications for comsats in non-Keplerian orbits that can be geostationary, but not limited to being over the equator. At this time, solar sails are the only technology that can be identified to meet the needs of these missions. In order to bring solar sails to a technology readiness level which can enable such missions with acceptable risk, a solar sail flight demonstration is needed within the next five years. The goal of the study described in this paper has been to define a reference solar sail demonstration mission which can be achieved for a reasonable cost within this time frame. This reference mission can then be used for costing and planning purposes, and as a comparison point to formal proposals to fulfill such a mission and pave the way for the science missions.

REQUIREMENTS AND GROUND RULES

The demonstration (demo) mission must deploy a flight capable sail film in a relevant space environment, achieve stable attitude control, demonstrate attitude control with a negligible expenditure of propellant, and achieve some measurable propulsive performance. Performance requirements have been developed for a representative NASA science missions which have been proposed on programmatic roadmaps. Some of the key driving requirements which derive from these mission studies are presented in Table 1.

TABLE 1. Key Driving Performance Requirements from NASA Mission Studies.

Point Design	Geostorm	Solar Polar Imager	Saturn Ring Observer
Sail Area (m^2)	5,000	10,000	100,000
Sail Subsystem Areal Density (g/m^2)	15	6	1
Sailcraft Areal Density (g/m^2)	50	12	22
Sail Pointing Accuracy (degrees)	3	1	1
Maximum Pitch/Yaw Acceleration (deg/s^2)	$2.3x10^{-9}$	$2.3x10^{-9}$	$2.3x10^{-9}$
Closest approach to sun (AU)	.9	.5	.3

Some key objectives of the sail demo mission are to observe and measure sail dynamics during deployment and operation, verify attitude control models, verify flight path control algorithms, and measure sail parameters that are difficult to model or ground test. In order to minimize risk on this first sail mission, there should be functional redundancy for components dependant on new technology, where practical, and the sailcraft should be able to recover from anomalous attitudes. The duration of the demo mission is currently planned to be no more than 3 months, although an extended mission is certainly possible.

TRADE STUDIES

Trade studies were performed in several key areas: sailcraft configuration, structural and mechanical implementation, and attitude control implementation.

Configuration Trades

The configuration trade space considered 3-axis controlled square sails, spin-stabilized disk sails (Garner, 2000), and the heliogyro (Blomquist, 1999). For the class of spin stabilized sails, we eliminated the heliogyro because it requires higher film stress, requires more active control to adjust the pitch of the individual blades, and because it was felt that the disk sail presented a technology path toward lower areal density for very large sails. Clearly the heliogyro warrants further study and analysis in the future, but we were limited in resources for this study and could only cover a limited trade space for our more detailed design studies. Representative cartoons of these sail types are shown in Figure 1.

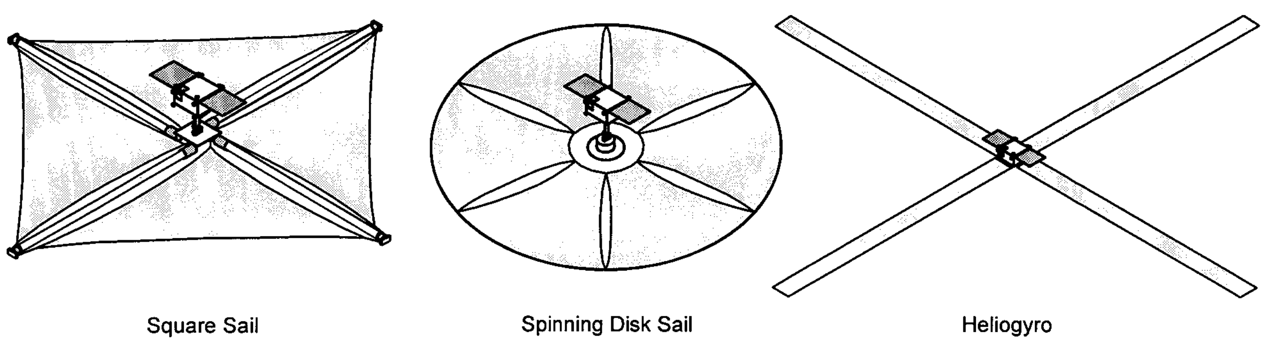

FIGURE 1. General Solar Sail Types (not to scale).

Point designs were developed for a 40 m wide square sail, a 100 m wide square sail, a 40 m diameter spinning disk sail, and a 100 m wide disk sail. For the disk sails, a segmented panel configuration was chosen over a solid disk because of packing and deployment control issues. The layout we arrived at ended up being very similar to the Russian Znamya sail, although our deployment scheme was somewhat different. Some key parameters of the four designs are presented in Table 2.

TABLE 2. Key Parameters from Sail Point Design Studies.

Point Design	Sail Area (m²)	Sail S/S Areal Density (g/m²)	Sailcraft Areal Density (g/m²)
40 m Square	1,400	29	111
100 m Square	8,800	14	27
40 m Disk	880	55	187
100 m Disk	5,500	13	34

From the point designs developed in this study, a trend was observed for areal density versus sail area for the square sail and the spinning disk sail. As depicted in Figure 2, square sails are more efficient for sail areas below about 50,000 m², and spinning disk sails are more efficient for larger areas. This is because the spinning sails in our study required more fixed overhead mass to support film deployment, tensioning, and control, and despinning some of the spacecraft elements. But the spinning sails become more efficient as they get larger, at the expense of being very difficult to turn due to their large inertia. On the other hand, the square sails based on purely cantilevered booms become less efficient as they become large enough to approach Euler column buckling limits.

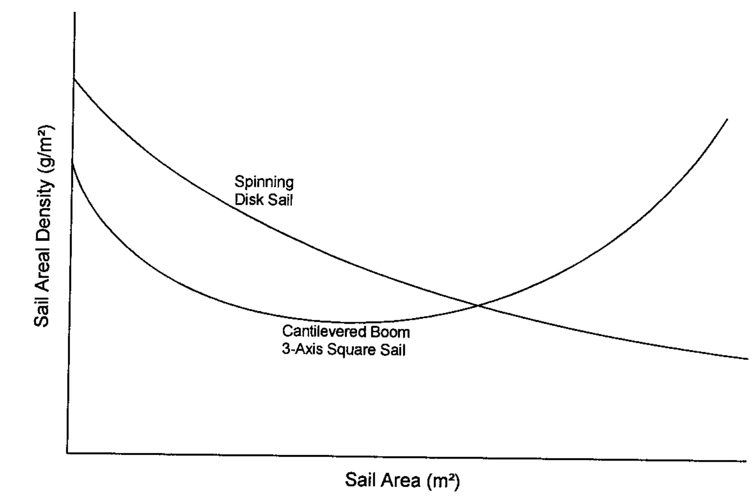

FIGURE 2. Trends in Areal Density versus Sail Area.

Many of the design decisions we made were driven by enabling a demo mission to be launched in the 2005 time frame, and technologies were chosen to minimize the development risk. For our reference design, we ended up choosing the square sail over the disk sail. The reasons for this are outlined in Table 3.

TABLE 3. General Configuration Trade Study.

Sail Type	Pros	Cons
3-Axis Square Sail	DLR and WSF ground deployment tests Slow controlled deployment Fast turn rates	Scaleable size for cantilevered booms limited to about 100,000 m² for reasonable implementations
Spinning Disk	Znamya flight data May enable lower areal densities for large sails Very stable safe mode	Difficult to test on ground Very slow turn rates Deployment is more difficult to control Difficult to control spin rate
Heliogyro	More controllable deployment Simple deployment mechanization	High film stress Higher areal density Very slow turn rates Complex control system Difficult to test control dynamics

Structural and Mechanical Design Trades

One of the most fundamental structural and mechanical trades was the implementation of the deployable booms for the square sail. Carbon lenticular foldable elastic tubes were chosen over inflatable booms because they are a more mature technology with well understood properties. We based our reference design on booms developed by DLR (Leipold, 1999) for a 40 m square sail which are at TRL 6, NASA terminology for being at the tested prototype stage. This design provides for storage of the rolled up booms on a single large central reel and a motor driven deployment that is well controlled.

We added a feature to the German design to enable jettisoning most of the deployment hardware after sail deployment. This approach is depicted in Figure 3 and provides for a lower mass, higher performance sailcraft.

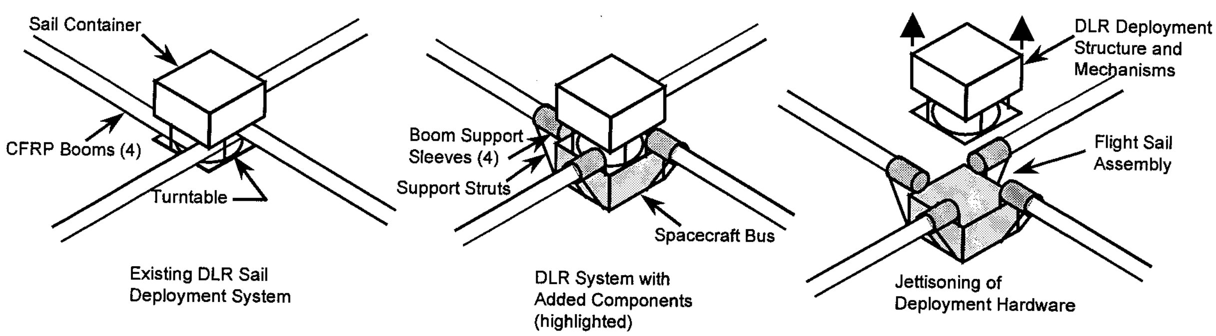

FIGURE 3. Concept for Jettisoning DLR Deployment Module.

In the reference design, the sail film is configured as four separate triangular panels, each supported with constant force springs at the outer two corners. Although perhaps not as structurally efficient, this approach was chosen over a single continuous sheet to simplify packaging and to provide more determinate structural support. The sides of the panels are not straight, but are large-radius arcs with a scallop angle of 4°, based on a trade study to minimize areal density, while maintaining a 7 kN/m² minimum film stress to reduce wrinkles and provide a smooth reflective surface.

Attitude Control Trades

A number of options for attitude control of the deployed sail were considered. Purely propellantless options were either based on shifting the center of mass relative to the center of pressure, or shifting the center of pressure relative to the center of mass. For the latter, we considered using articulated vanes and also articulating the sail panels themselves to achieve pitch, yaw, and roll control. Articulating the sail panels appeared more promising than vanes, because the mechanical implementation was simpler, there was less hardware to deploy, and hence less mass and cost.

For the options involving shifting the center of mass relative to the center of pressure, we focused on articulating the entire spacecraft bus relative to the sail subsystem in order to move the largest possible mass and maximize control authority. The options considered were translating the bus in the plane of the sail and also rotating the bus on a short boom extended from the plane of the sail. The latter option was preferred because it was viewed as having a simpler mechanical implementation, and because torques to the sail subsystem could be minimized, presenting a more stable dynamic environment for the sail.

Ultimately, we selected the bus articulation on a boom rather than articulating the sail panels, because it minimized the complexity of the sail subsystem, and it also provided an implementation that could be readily adapted to many different sail designs, including spinning sails. The bus rotation is effected via reaction wheels, minimizing the disturbance input to the sail subsystem dynamics. Once the bus is rotated to the desired control position, the boom is locked with a mechanical clutch to hold position. Sail rotation control is achieved via the reaction wheels, with chemical thrusters to unload the wheels.

REFERENCE SAILCRAFT DESIGN

The reference design is depicted in Figure 5.

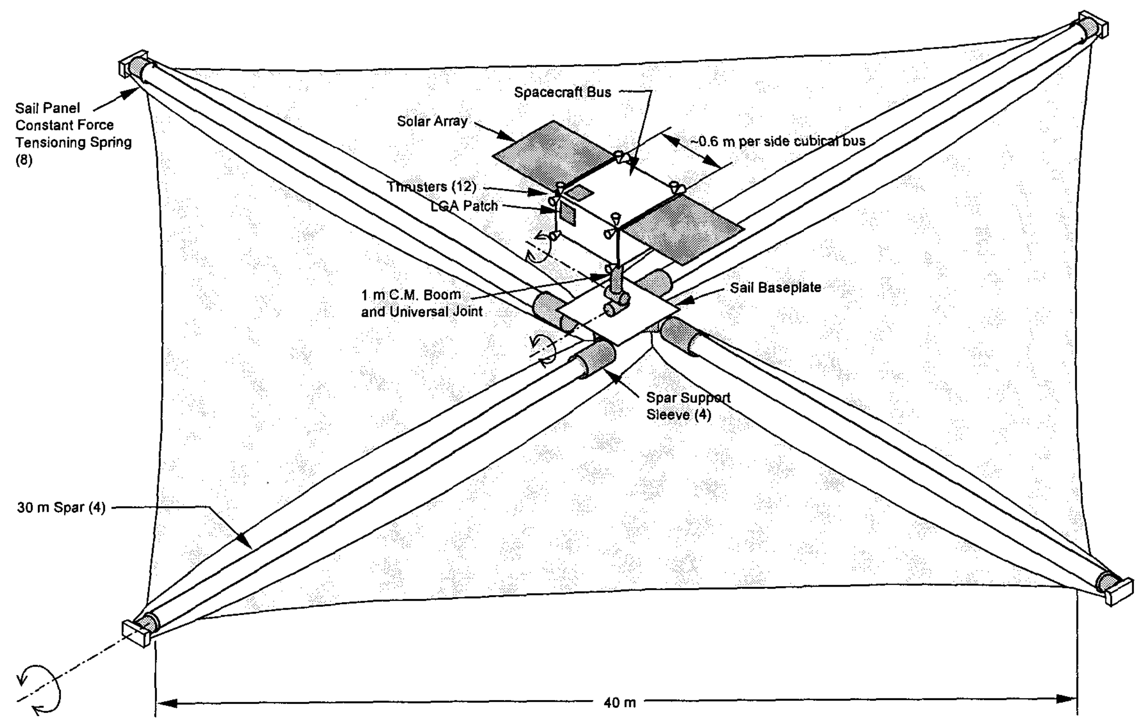

FIGURE 5. Solar Sail Reference Configuration (not to scale).

A block diagram is provided in Figure 6. A commercial microspacecraft bus was assumed as the basis for the avionics. The avionics are driven by the requirements in Table 3 needed to support deployment, control, interfaces, data acquisition, and timely downlink of needed data.

TABLE 3. Sailcraft Avionics Requirements.

Parameter	Requirement
processor speed	50 mips
computer memory	32 MB
data storage	5 Gb
number of high rate data ports	10
number of low rate data ports	100
internal data rate	5 Mb/sec
number of power switches	50
number of pyro switches	70
power generation	200 W
power throughput	200 W
electrical energy storage	500 W-hrs
downlink data rate	2 Mb/sec
uplink data rate	2 kb/sec
number of antennas	3

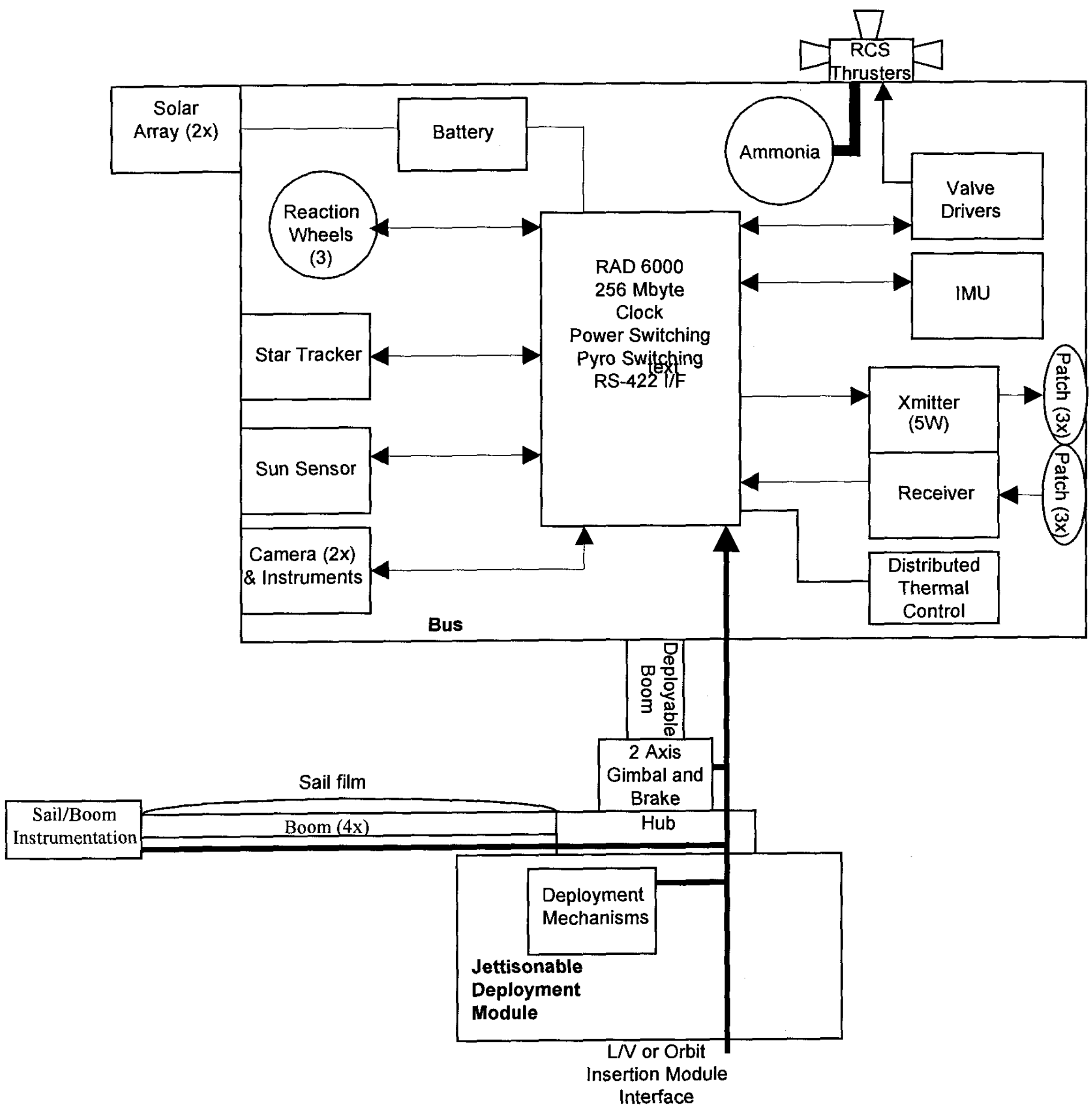

FIGURE 6. Solar Sail Reference Block Diagram.

A top level mass list by subsystem is provided in Table 4. The sail film is assumed to be 1 μm kevlar reinforced aluminized mylar. This material has been produced at a thickness of 2.5 μm, and no technical hurdles are foreseen in producing the 1 μm material. Notice that the sail film itself is a small fraction of the sailcraft mass, and that other spacecraft elements may be more fruitful targets of a mass reduction effort, rather than the sail film.

TABLE 4. Sailcraft Mass Breakdown by Subsystem.

Subsystem	Mass, including contingency (kg)

MISSION DESIGN OPTIONS

For a solar sail demonstration mission, it is important to be in a flight regime where the solar pressure is much greater than the drag from the Earth's atmosphere. To meet cost constraints, the main launch options being considered are as a secondary payload on a commercial or government launch, or from the Space Shuttle with an additional chemical propulsion system to get into a higher orbit. Orbits considered were MEO, GTO, or GEO.

In order to demonstrate propulsive performance several options were considered including spiraling out to increase the orbital radius, effecting plane changes, or demonstrating a levitated orbit.

CONCLUSIONS

Our preliminary studies have indicated that a demonstration mission of a fully operational solar sail can be undertaken in the next few years with minimal development risk. Our reference design gives us confidence that sail subsystem areal densities of 14 g/m^2 or less can be achieved in the near term, enabling such important and unique missions as Geostorm and Solar Polar Imager. Preliminary analyses have indicated that square sails with purely cantilevered booms can be built as large as 20,000 m^2, and by attaching four of these sails together, a derivative of this technology can be built as large as 80,000 m^2. Other near term mission possibilities utilizing this level of sail technology include a pole sitter to hover over the north pole, a geotail mission to explore the earth's magnetic tail, and fast flyby missions to the outer planets or to the Kuiper belt.

NOMENCLATURE

comsat = communication satellite
demo = demonstration
GEO = Geostationary Earth Orbit
GTO = Geosynchronous Transfer Orbit
kN = kilonewtons (1,000 newtons)
m = meter
μm = micrometer
MEO = Medium Earth Orbit
S/S = subsystem
TRL = Technology Readiness Level (1-10, with 10 being highest)

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